**Naval Surface Warfare Center**
**Carderock Division**
West Bethesda, MD 20817-5700

**NSWCCD-CISD–2011/009** August 2011
Ship Systems Integration & Design Department
Technical Report

# TriSWACH Small Model Testing

By:
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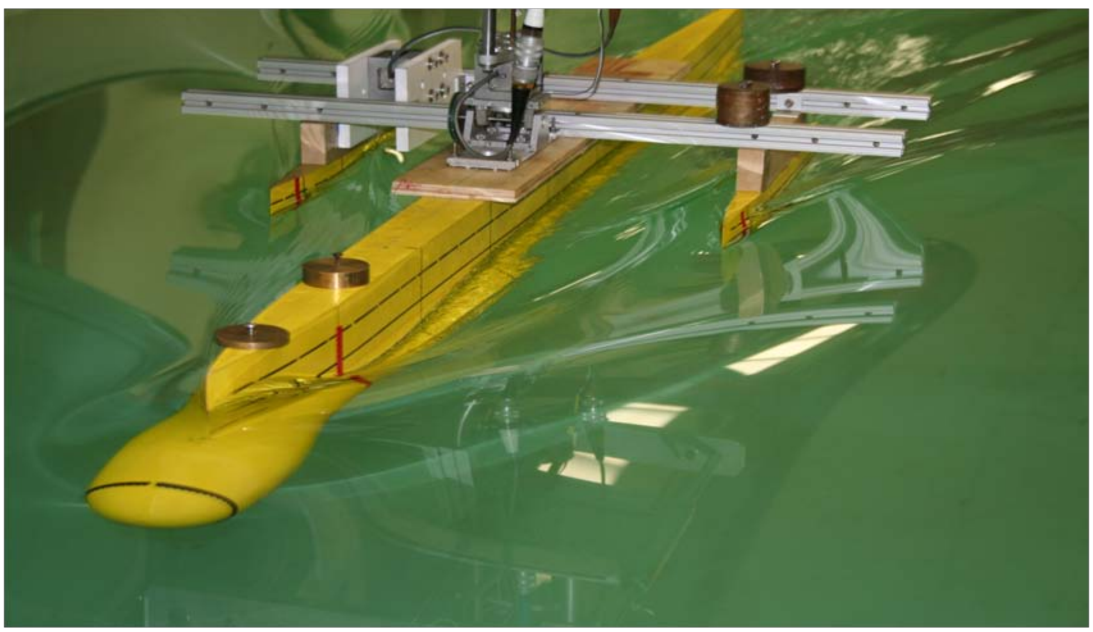



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# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*



**1. REPORT DATE** *(DD-MM-YYYY)*
05-08-2011

**2. REPORT TYPE**
Final

**3. DATES COVERED** *(From - To)*
05-23-2011 – 08-05-2011

**4. TITLE AND SUBTITLE**
TriSWACH Small Model Testing

**5a. CONTRACT NUMBER**

**5b. GRANT NUMBER**

**5c. PROGRAM ELEMENT NUMBER**

**6. AUTHOR(S)**
Andrew Harrington
Joseph Daniel Wells

**5d. PROJECT NUMBER**

**5e. TASK NUMBER**

**5f. WORK UNIT NUMBER**

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADDRESS(ES)**
Naval Surface Warfare Center Carderock Division
9500 Macarthur Boulevard
West Bethesda, MD 20817-5700

**8. PERFORMING ORGANIZATION REPORT NUMBER**
NSWCCD-CISD–2011/009

**9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
Chief of Naval Research
One Liberty Center
875 North Randolph Street,
Suite 1425
Arlington, VA 22203-1995

**10. SPONSOR/MONITOR'S ACRONYM(S)**

**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

**12. DISTRIBUTION / AVAILABILITY STATEMENT**
DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited

**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**
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**15. SUBJECT TERMS**
TriSWACH, trimaran small waterplane area centerhull, model test, resistance

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| | | | | | Colen Kennell |
| **a. REPORT** | **b. ABSTRACT** | **c. THIS PAGE** | SAR | 31 | **19b. TELEPHONE NUMBER** *(include area code)* |
| UNCLASSIFIED | UNCLASSIFIED | UNCLASSIFIED | | | 301-227-5468 |

## Abstract

*The ACCeSS community is interested in understanding the capabilities of the Trimaran-Small Water Plane Area Center Hull (TriSWACH) ship concept and the future use of this concept for the United States Navy. The aim of this project was to conduct resistance, sinkage, trim, and seakeeping tests for a variety of sidehull configurations on the TriSWACH model constructed at Webb Institute, in the Naval Academy's 120ft tow tank facility. Calm water and limited regular wave testing was previously completed at Webb institute and Steven's Institute of Technology, but irregular wave tests had not been performed. This project conducted calm water resistance tests for selected sidehull locations, varied transversely and longitudinally, to correlate with data from previous testing at Webb Institute. To gather the data necessary to study the effects of interference between the hulls, the centerhull and the sidehulls were tested separately. To observe the effect of splayed sidehulls, calm water resistance tests were conducted with the sidehulls splayed 0.5 and 1.5 degrees outboard. Calm water resistance tests were also conducted using sidehulls with double the displacement of the original sidehulls. Regular wave tests at Froude no. 0.3-0.5 and irregular wave tests in sea state 4-5 were completed for selected sidehull configurations. The tow tank data collected can validate CFD hull form optimization tools as well as support powering predictions for the TriSWACH design.*

## Acknowledgements

This project would not have been possible without a great deal of help. We would like to sincerely thank all of the following people for their advice, guidance, and expertise.

Bill Beaver – USNA

Jaye Falls PhD – USNA\ACCeSS

Jenny Kelso – CISD

Colen Kennell – CISD

Steve Ouimette – CISD

Mark Pavkov- USNA

Dan Rhodes – USNA

Justin Ryan – CISD

Greg White PhD – USNA

John Zseleczky – USNA

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# Notation

| | |
|---|---|
| ACCeSS | Atlantic Center for Innovative Design and Control of Small Ships |
| AP | Aft perpendicular |
| $C_A$ | Correlation Allowance |
| CAD | Computer-aided design |
| $C_r$ | Residuary Resistance Coefficient |
| $C_t$ | Total Resistance Coefficient |
| EHP | Effective Horse Power |
| FP | Forward perpendicular |
| Fr | Froude Number |
| g | Gravitational Constant |
| $GM_T$ | Transverse Metacentric Height |
| ITTC | International Towing Tank Conference |
| LCF | Longitudinal Center of Flotation |
| LCG | Longitudinal center of gravity |
| LOA | Length over all |
| LT | Long Ton |
| LWL | Length at water line |
| NAVSEA | Navel Sea System Command |
| no. | number |
| NREIP | The Naval Research Enterprise Intern Program |
| ONR | Office of Naval Research |
| Rn | Reynolds Number |
| SIT | Stevens Institute of Technology |
| TriSWACH | Trimaran - Small Water Plane Area Centerhull |
| VCG | Vertical center of gravity |

# Introduction

## Background

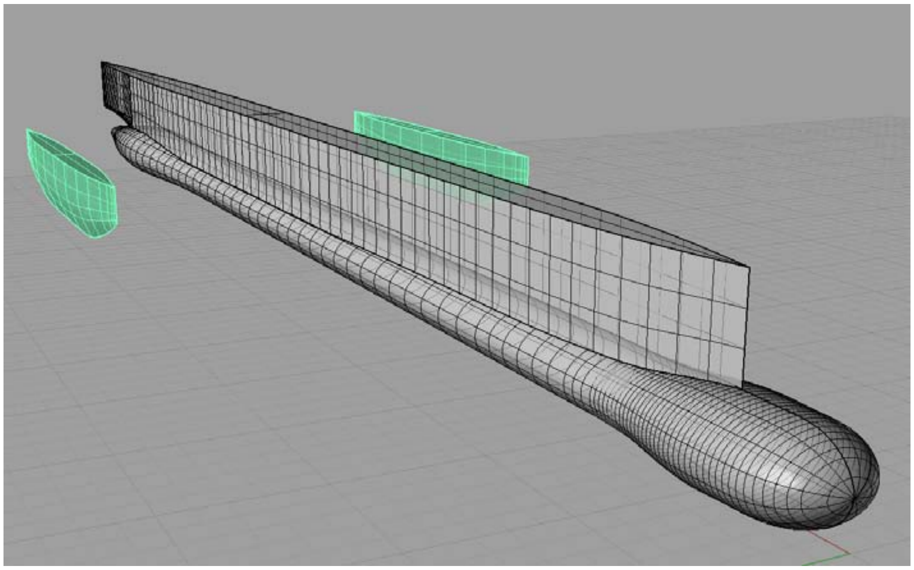

**Figure 1: Tri-SWACH Hull Form**

The Tri-SWACH, Trimaran-Small Waterplane Area Center Hull, is a novel hull form concept that is being investigated by ONR and by the ACCeSS team. The Atlantic Center for the Innovative Design & Control of Small Ships has previously completed various tow tank tests, as well as begun development of CFD optimization tools for the Tri-SWACH hull form. The Tri-SWACH is a trimaran vessel with a Small Waterplane Area Twin-Hull (SWATH) style center hull and traditional sidehulls. The design objective of the SWATH center hull is to improve seakeeping performance. The high length-to-beam ratio of the center hull reduces high speed resistance and improves powering efficiency. The trimaran design offers a larger available deck area over a similarly sized monohull vessel. One suggested future use of the Tri-SWACH hull form is a UAV carrier, for which large available deck area and good seakeeping will be critical.

## Objectives

A primary objective of this project was to expand the testing database for the Tri-SWACH hull form in calm water and both regular and irregular waves. The previous calm water testing with various sidehull locations had been done at the Webb Institute and Stevens Institute of Technology (SIT). SIT also completed minimal regular wave testing. For this project, which utilized the USNA Hydrodynamics lab's 120ft Tow Tank facility, calm water tests were completed for two different sidehull locations for both the original sidehulls as well as a second set of larger sidehulls with double the displacement of the originals. The USNA calm water testing with the original sidehulls was completed using the same sidehull locations and through a similar speed range as the previous testing by SIT, to observe correlation between the data sets as well as to validate testing procedure. Additional calm water tests were performed to investigate the effect of splaying the sidehulls, a previously untested condition. Other objectives were to obtain data necessary for studying the interference between the hulls of the TRI-SWACH, as well as to supply data for evaluation of CFD hull form optimization tools. A final goal was to utilize the resistance data gathered to support powering predictions for the concept hull design.

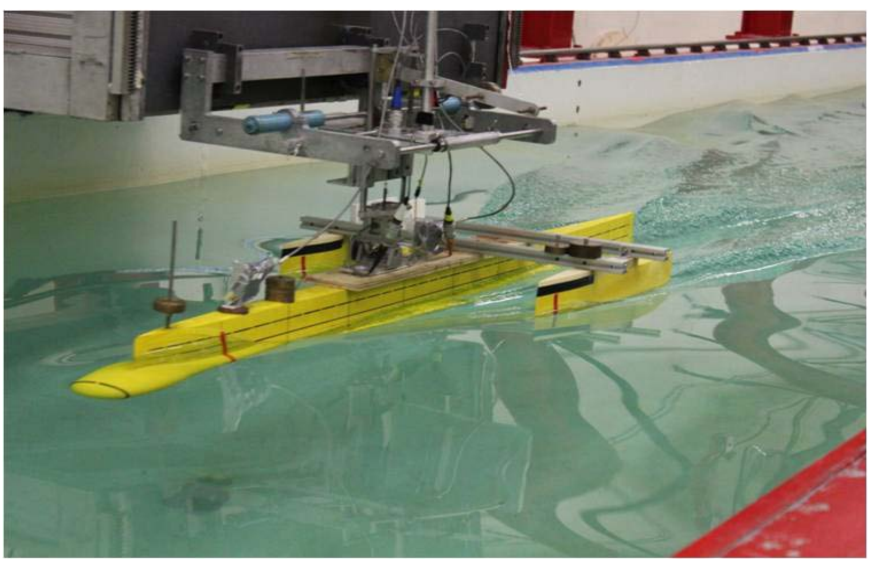

**Figure 2: Tri-SWACH Model during Data Collection Run**

# Tri-SWACH Model

### Description and Characteristics

The Tri-SWACH model can be seen below in Figure 3 with the original sidehulls attached. The model was designed to allow transverse and longitudinal variation of the sidehull position, and was built to ONR specifications. The sidehulls are attached to the model via two extruded aluminum crossbeams. The transverse location of the sidehulls can be changed both inboard and outboard by sliding them in a groove on the cross beams. The longitudinal position of the sidehulls can be changed forward and aft by moving the entire crossbeam/sidehull setup forward or aft on the wooden mounting plate. SIT developed a second set of larger sidehulls with double the displacement of the originals, and these sidehulls were incorporated into this project's test matrix to explore the resistance characteristics as well as the seakeeping properties of the larger sidehulls. The principal characteristics for the model and its components can be found in Table 1.

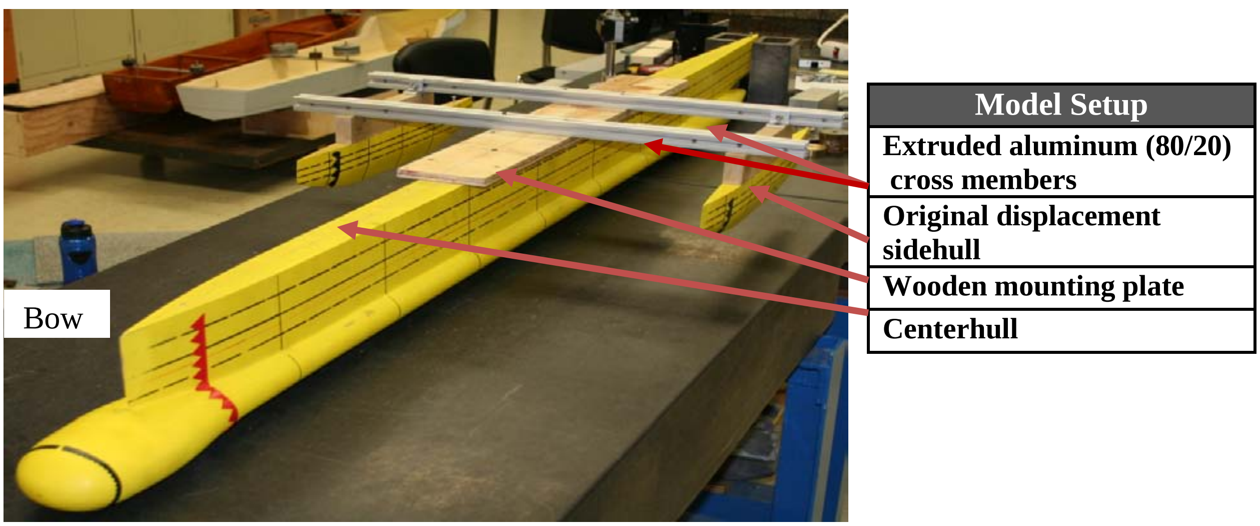


**Figure 3: Tri-SWACH Model**

**Table 1: Principal Characteristics**

| Parameter | | Units |
|---|---|---|
| Centerhull LOA | 84.109 | in |
| Centerhull LWL | 79.593 | in |
| Centerhull Max Beam | 4.406 | in |
| Original Sidehulls LWL | 21.480 | in |
| Original Sidehulls Max Beam | 1.073 | in |
| DD Sidehulls LWL | 27.200 | in |
| DD Sidehulls Max Beam | 1.355 | in |
| Model Displacement w/(Original Sidehulls) | 28.400 | lbs |
| Model Displacement w/(DD Sidehulls) | 30.850 | lbs |

## Sidehull Positions

The TRI-SWACH model can be configured to have nine different sidehull location configurations by varying the longitudinal and transverse positions. The possible sidehull positions are shown in Figure 4. The mid longitudinal position of the sidehull was specified by ONR to be one inch aft of the LCF, with the forward and aft longitudinal positions being 10% of the length of the center hull forward and 10% of the length aft from the mid position. The mid transverse position was specified by ONR to provide a vessel $GM_T$ equal to 10% of the total beam, and the inboard and outboard positions are 10% of the total beam inboard and 10% of the total beam outboard from the mid position. (Justin Klag)

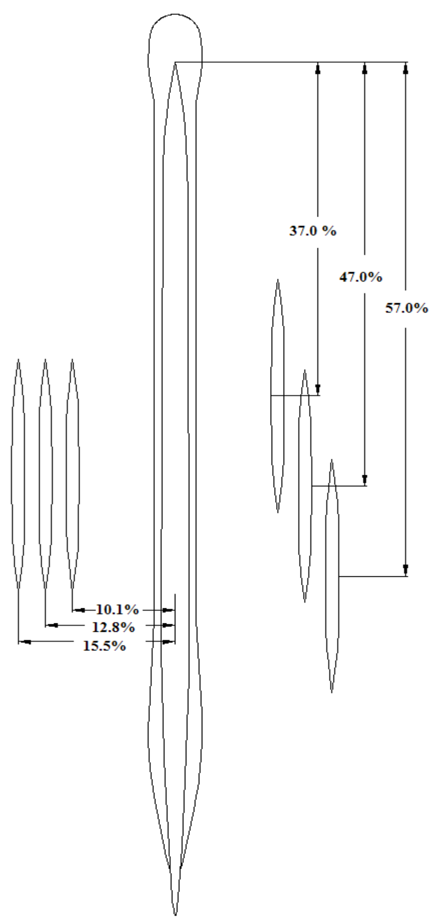


**Figure 4: Sidehull Positions**

## Model Setup

This project involved a very large number of data collection runs, as well as a large number of model configuration changes. This led to concern about the repeatability of the experimental setup. To ensure the sidehulls would be in the correct position for each configuration change, two indexing blocks were designed and built. These blocks, one of which is shown in Figure 5, are foam blocks with three vertical grooves cut into them. The grooves are cut such that when the indexing block is married with the parallel mid-body of the center hull, the center of the groove is the correct distance from the center line of the center hull. One block is placed forward of the FP of the sidehull and one aft. When the perpendiculars are in the designated groove for the given configuration, the sidehull is in the correct location transversely. The vertical grooves in the indexing blocks also prevent camber in the sidehulls. To assure no camber would be induced while the model was being towed, the original 1” by 1” angle bracket used to attach the sidehull to the cross beams was replaced by a 1” by 6” angle bracket. This additional strength prevented the angle bracket, and thus the sidehull, from rotating. The larger angle bracket can be seen in Figure 5. The CAD drawing of the indexing blocks is in Appendix A.

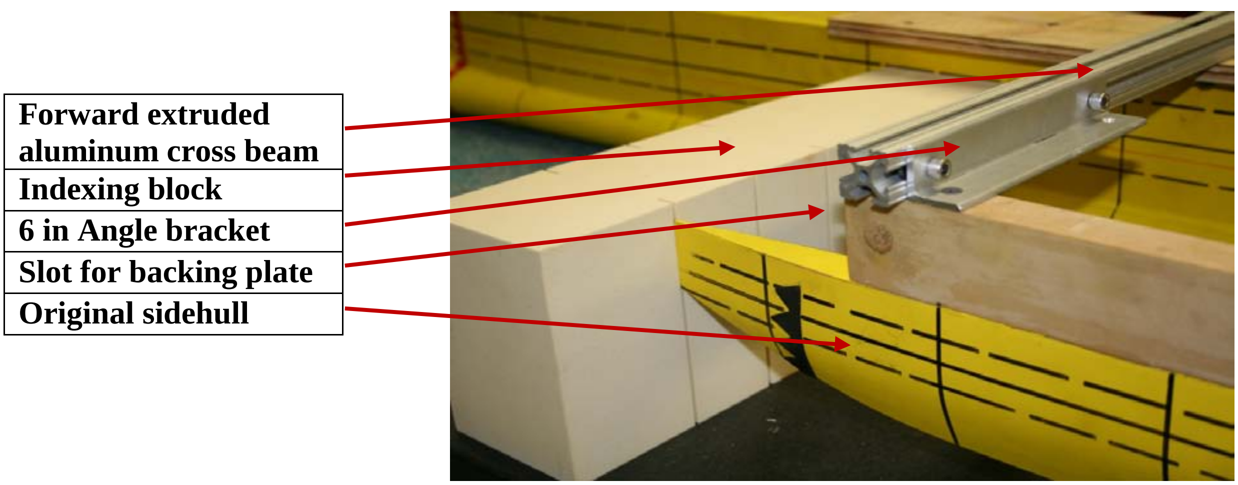


**Figure 5: Model Setup**

With the model setup built by Webb institute the sidehulls were attached to the extruded aluminum cross beams via a through bolt mount which did not allow for transverse movement of the sidehulls. The through bolt was replaced with a shorter bolt and a backing plate which allowed the sidehulls to slide inboard and outboard and allowed for the use of the indexing blocks.

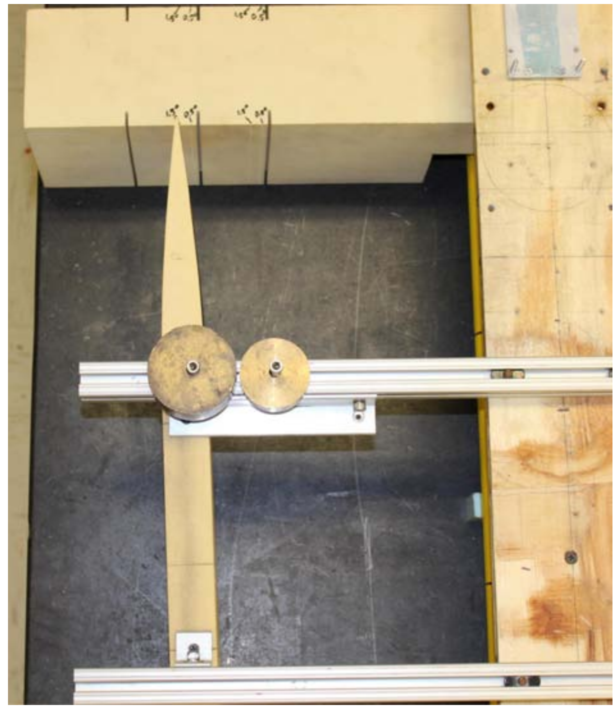

**Figure 6: Splayed Sidehull Using Indexing Block**

## Splayed Sidehull

Additional calm water data collection runs were conducted with the original sidehulls splayed outboard. The purpose of these tests was to see if by splaying the sidehulls outboard, the sidehulls would interact with the bow wave from the center hull and create lift. These tests were run with the model having the sidehulls in the aft-mid and mid-inboard locations, with the FP of the sidehulls splayed outboard 0.5 and 1.5 degrees. The AP of the sidehulls was kept stationary to maintain a minimum distance from the center hull. This splay was quantified using the indexing blocks the team designed. The correct distance from the center hull center line was scored into the indexing blocks for the two splayed conditions. When the FP of the sidehull was in the scored line the indexing block ensured the correct amount of splay.

**Table 2: Splayed Sidehull Properties**

| Splay (Original Sidehulls) | | |
|---|---|---|
| **Degrees of Splay (Outboard)** | **0.5°** | **1.5°** |
| **Distance From Origin** | **0.187 in** | **0.562 in** |

## Hama Strips

Hama strips were used for turbulence stimulation. The Hama strip on the bulbous bow, shown in Figure 7**,** did not need to be replaced when the model arrived. However, the other Hama strips on the model near the bow were no longer in usable condition. The team built new Hama strips in accordance with guidance from the staff of the USNA Hydrodynamics lab. These Hama strips were placed at the first station (10% of the LWL aft of FP) for the center hull and the sidehulls. Information on the construction of the Hama strips can be found in Appendix B.

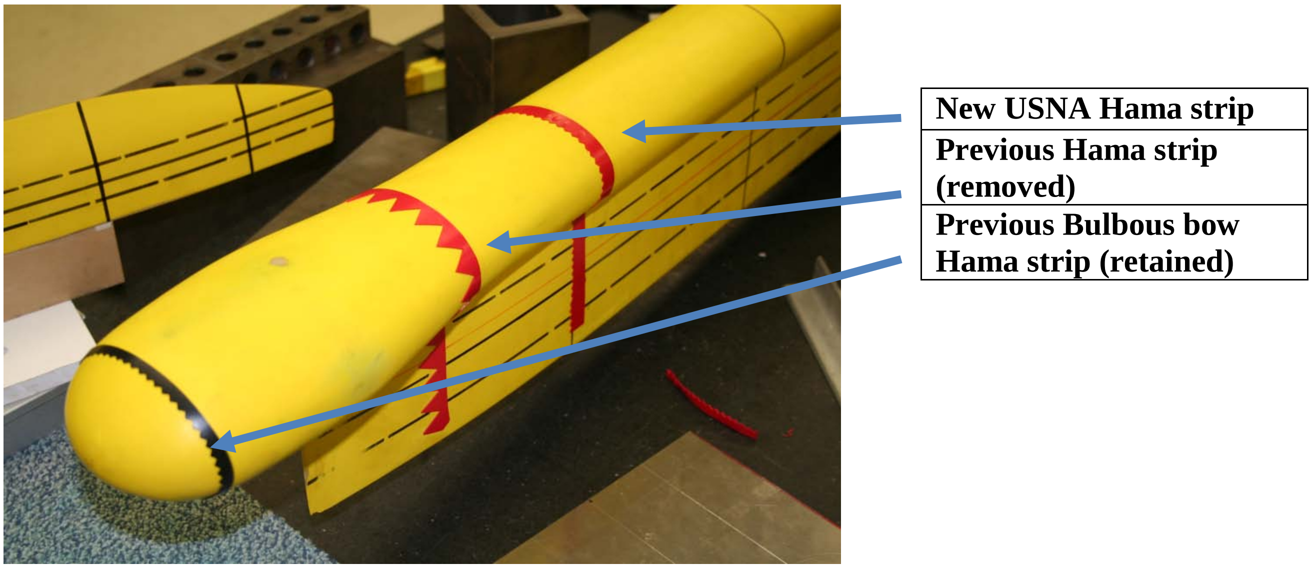


**Figure 7: Center Hull Hamma Strips**

## Ballasting

The displacement of the model with the original sidehulls is 28.4 lbs. To achieve this displacement with the model properly ballasted in all sidehull configurations the model was towed forward of the LCG. By moving the weight associated with the towing apparatus forward, the bow-up trim associated with the aft longitudinal sidehull configuration was corrected. The waterline for the center hull was kept constant in both the original sidehull configuration and the double-displacement sidehull configuration. This was done to aid the validation of CFD hull form optimization tools. The displacement necessary to keep the same waterline with the double displacement sidehulls is 30.85 lbs.

## Gyradius Testing

The longitudinal gyradius is the measure of the longitudinal weight distribution about the center of gravity. The Lamboley method was used for finding the longitudinal gyradius as well as the LCG and VCG. The team received guidance that a realistic value for the gyradius of the model (and ship) is about 25% of the length between perpendiculars. (White) The gyradius of the model was found for each ballasting condition and the ballast adjusted accordingly to ensure an acceptable value for the gyradius.

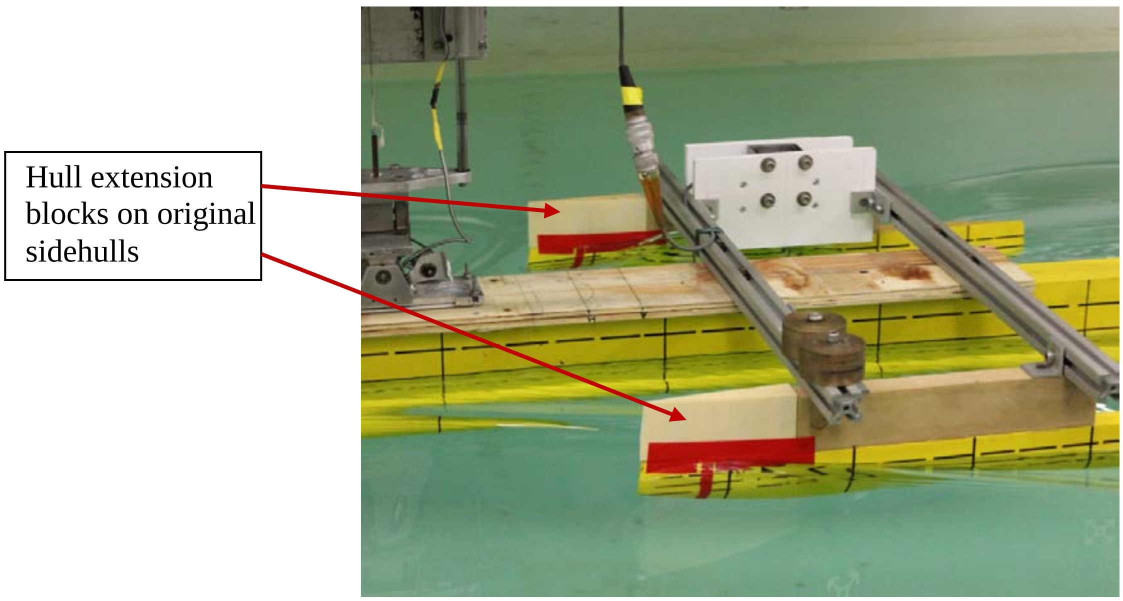


**Figure 8: Sidehull Extension Blocks**

## Bow Extensions

During certain testing conditions spray impinged on the deck of the sidehulls. To prevent unrealistic resistance values, foam bow extensions were installed to raise the level of the deck. The sidehull bow extensions can be seen in Figure 8.

## Test Equipment and Instrumentation

Total resistance, sidehull resistance, heave, pitch, velocity, vertical acceleration at the LCG and bow, and wave height data was collected. The sensors were located on the model, except for the wave gauge which was mounted midway down the tank and the sonic wave probe which was

mounted on the carriage just ahead of the model. The sonic wave probe collected wave height data for the waves the model encountered. The model was fixed in roll, but free in heave and pitch. The accelerometers were only used during seakeeping tests. All of the gauges were calibrated prior to testing. The calibration information and gauge specifications can be found in Appendix C. Video and still images were taken of the model setup and during data runs.

| Instrument | Quantity | Units |
|---|---|---|
| Heave Post | Heave | in |
| Block Gauge 1 (Cal. 7 lbs) | Total Model Resistance | lbs |
| Pitch Pivot | Pitch | deg |
| Bow Accelerometer (10.85in aft of the FP) | Vertical Accelerations | g's |
| Wave Gauge (not seen in picture) | Wave Height | in |
| Ultrasonic Distance Sensor (not seen in picture) | Wave Height | in |
| LCG Accelerometer | Vertical Accelerations | g's |
| Block Gauge 2 (Cal. 2 lbs) | Sidehull Resistance | lbs |

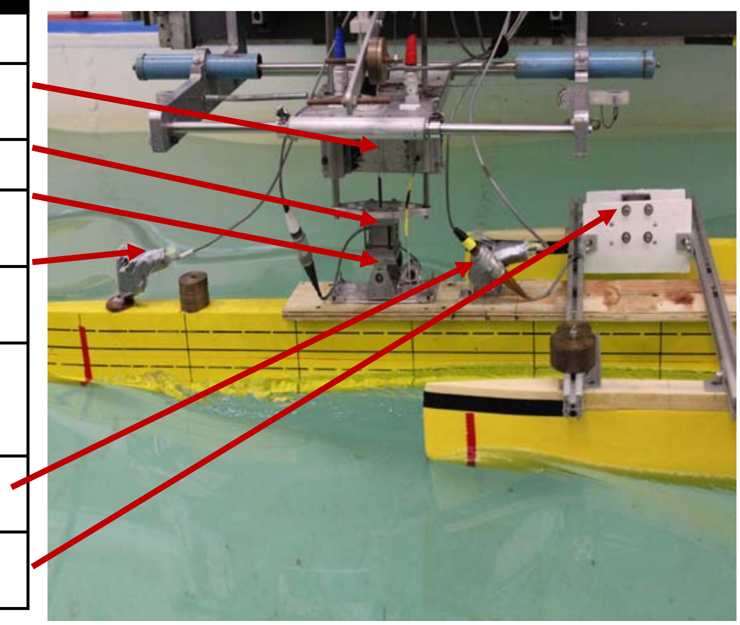

**Figure 9: Model Instrumentation**

## Testing

Due to tank availability, testing could not begin until the 5th week of the project. This left the team ample time to setup the model and make the necessary changes to the model for the desired repeatability of experiment. The Excel document used for real-time data analysis and scaling was also developed during this time. The first iteration of the testing matrix developed by ACCeSS involved over 600 tests, but due to time constraints and prioritization it was pared down to the final number of 307 successful data collection runs. The final test matrix is given in Table 3 below.

**Table 3: Test Matrix**

| Configuration | Splay | Sidehull | Fn Range | Runs | Condition |
|---|---|---|---|---|---|
| Center hull only | none | none | 0.1 - 0.6 | 24 | calm |
| one sidehull only | none | original | 0.1 - 0.6 | 21 | calm |
| mid-inboard | none | original | 0.1 - 0.6 | 26 | calm |
| aft-mid | none | original | 0.1 - 0.6 | 28 | calm |
| mid-inboard | 0.5 deg | original | 0.1 - 0.6 | 27 | calm |
| aft-mid | 0.5 deg | original | 0.1 - 0.6 | 26 | calm |
| mid-inboard | 1.5 deg | original | 0.1 - 0.6 | 26 | calm |
| aft-mid | 1.5 deg | original | 0.1 - 0.6 | 15 | calm |
| mid-inboard | none | double | 0.1  0.6 | 25 | calm |
| aft-mid | none | double | 0.1  0.6 | 28 | calm |
| aft-mid | none | double | 0.3, 0.5 | 42 | regular waves |
| aft-mid | none | double | 0.3, 0.5 | 12 | sea state 4 |
| aft-mid | none | double | 0.3, 0.5 | 7 | sea state 5 |
| | | | **Total Runs** | 307 | |

## Calm Water Testing

Calm water data collection runs were completed for Fr nos. 0.1 to 0.6, alternating between high and low speed runs. The first testing was for the original sidehull only and the center hull only. This data was gathered to study the interference between the hulls, which will be explored further by the ACCeSS team in the future. The model with the original sidehulls was tested in the aft-mid and mid-inboard configurations as previously tested at SIT, to observe correlation between the two sets of data and validate testing results. The model with the double displacement sidehulls was originally to be tested in all nine possible positions but, due to time constraints, was tested in only the aft-mid and mid-inboard positions. These two configurations were chosen based on previous reports that these were the optimal positions and also to keep the configurations tested consistent.

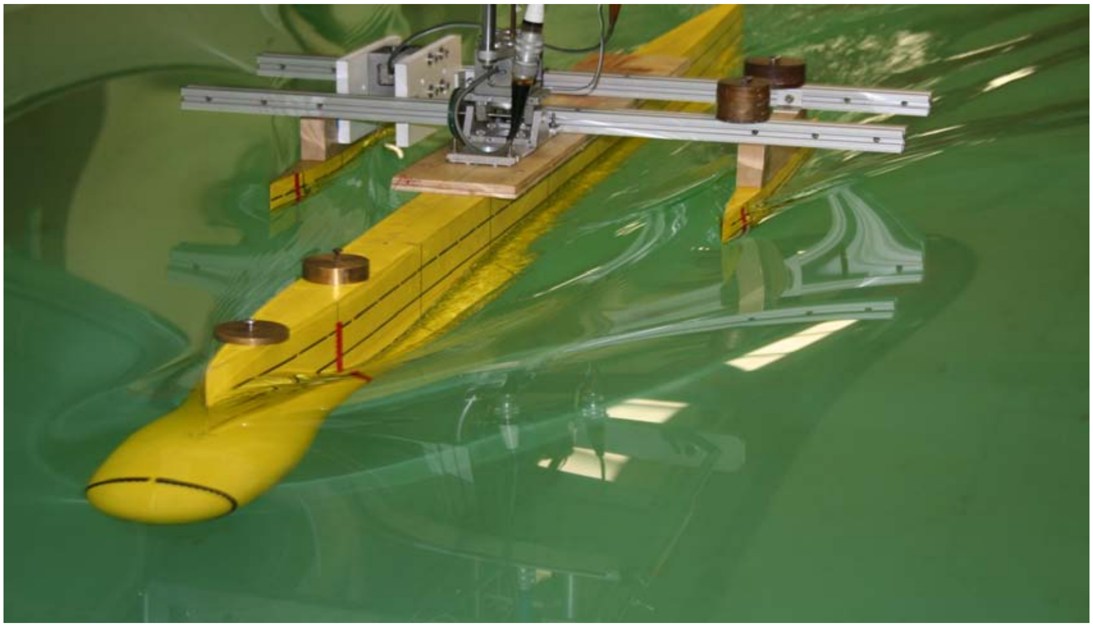

**Figure 10: Mid-Inboard Original Sidehulls Calm Water Run**

Calm water testing with the sidehulls of the model splayed outboard was also completed through the same speed range, Fr. nos. 0.1 - 0.6, and in the aft-mid and mid-inboard configurations. Total resistance, sidehull resistance, heave, and pitch data was recorded for each run, but acceleration and wave height data was only collected for seakeeping tests.

**Table 4: Calm Water Test Speed Range**

| Froude no | Model Velocity ft/sec | Ship (1,000 LT) Velocity (knots) |
|---|---|---|
| 0.1 - 0.6 | 1.461 - 8.763 | 5.67 - 34.04 |

## Seakeeping Tests

The model with the double displacement sidehulls was tested in both regular and irregular waves. Another team within ACCeSS had plans to complete seakeeping testing with the original sidehulls and no seakeeping testing had ever been done with the double displacement sidehulls. The seakeeping testing progressed much slower than the calm water testing because the amount of time needed for the water in the tank to calm down increased dramatically. The average wait time between runs went from around three minutes for the calm water runs to around 15 minutes for the testing in waves. Acceleration data was gathered during seakeeping testing, with one

accelerometer at the LCG and one forward. The placement of the accelerometers can be seen in Figure 9. Wave height data was collected via a wave gauge midway down the tank and a sonic wave probe mounted on the carriage just forward of the model. Instrument specifications can be found in Appendix C.

**Regular Waves**

Regular wave testing was completed at Fr nos. 0.3 and 0.5 for a series of frequencies and wave heights. These speeds were chosen by the ACCeSS team based on anticipated ship operating speeds. The frequency and wave height range tested are given in Table 5.

**Table 5: Regular Wave Testing Parameters**

| Property | Model | Ship (1,000 LT) |
|---|---|---|
| **Input Speeds** | 4.35 ft/sec | 17 knots |
| | 7.26 ft/sec | 28 knots |
| **Wave Period** | 0.71-2.50 sec | 4.66-16.39 sec |
| **Wave Height** | 0.017-0.179 ft | 0.749-7.713 ft |

**Irregular Waves**

Irregular wave testing was completed at Froude nos. 0.3 and 0.5 for North Atlantic sea states 4 and 5. The original testing matrix called for sea states 2 and 4, but was modified to sea states 4 and 5 after seeing minimal response in sea state 2. The wave spectra for each sea state was generated using the ITTC recommended Bretschneider spectrum significant wave height and modal period. The starting time for the model tests was staggered to ensure the model encountered the full wave spectrum throughout the testing runs. The significant wave heights and modal periods used are listed in Table 6. The sea states are defined in Appendix D.

**Table 6: Irregular Wave Testing Properties**

| Property | Model | 1,000 LT Ship |
|---|---|---|
| Input Speeds | 4.35 ft/s | 17 knots |
| | 7.26 ft/s | 28 knots |
| North Atlantic Sea States | 4 & 5 | 4 & 5 |
| SS 4 Mean wave height | 0.143 ft | 6.15 ft |
| SS 4 Modal wave period | 1.342 s | 8.8 s |
| SS 5 Mean wave height | 0.248 ft | 10.65 ft |
| SS 5 Modal wave period | 1.479 s | 9.7 s |

# Results and Analysis

A very large amount of data was collected during this project. The calm-water results and analysis will be discussed first, followed by the seakeeping test results.

## Calm Water Testing

All calm water tests were run with the aft-mid and mid-inboard sidehull positions for a speed range corresponding to Froude numbers from 0.1 to 0.6. The measured wave making resistance data is plotted as the non-dimensionalized coefficient of residuary resistance (Cr) against Froude number. Measured data from this project is labeled “USNA” in the plots. During testing some speeds were run multiple times to check for repeatability of the measurements.

### Correlation between USNA and SIT Testing

The calm water tests with the original sidehulls were run to correlate with the previous testing done at SIT. The same model sidehull positions and similar speed ranges were used. However, the turbulence stimulation was different between the two tests because the Hama strips used during the SIT tests were no longer on the model. Therefore new Hama strips had to be made and attached to the model. Another difference was that for this project the model was tested over

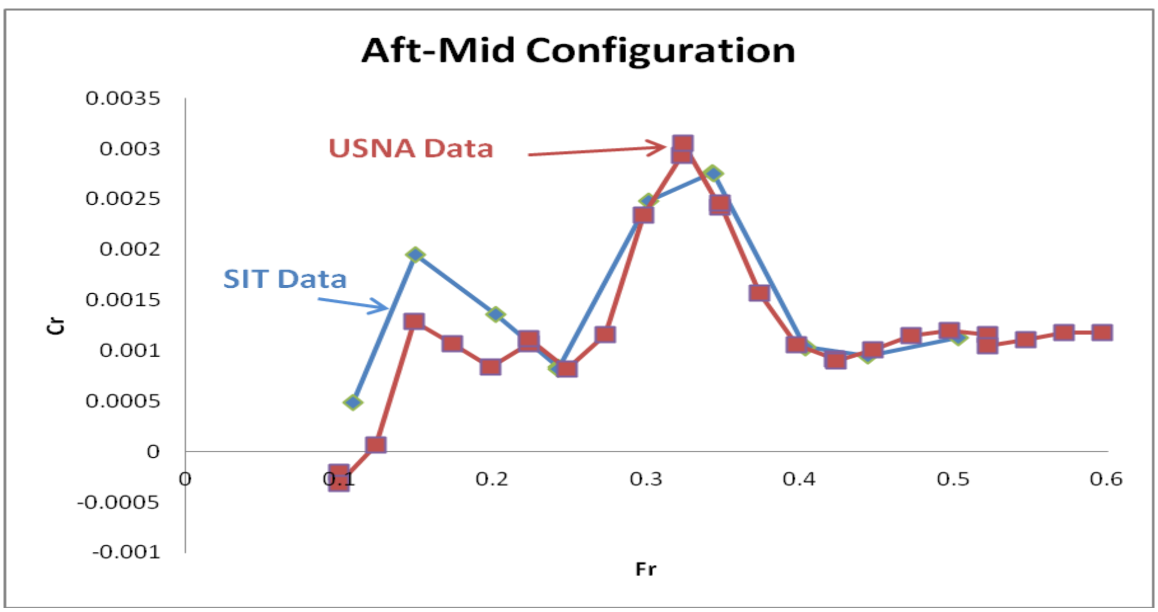


**Figure 11: Calm Water Towing Tank Correlation for Aft-Mid Location**

a larger speed range and data was sampled with a higher frequency. SIT had towed the model from the LCG, but to achieve correct ballasting in all configurations for this project, the model was towed forward of the LCG. It can be seen from Figure 11 that there is good trending between the two lines for the aft-mid sidehull configuration above Fr no. 0.25. The differences between the data below Fr no. 0.25 could be attributed to inconsistent turbulence stimulation. An indicator that this may be the case is the negative value obtained for Cr for the USNA data. This could be caused by laminar flow, which would skew the data. The peak resistance for the USNA data is larger than that of SIT, but that may attributed to SIT not testing at that speed.

Figure 12 shows $C_r$ against Froude no. for the SIT and USNA data for the mid-inboard sidehull configuration. Again, there is good correlation between the data at higher Froude nos. but not below a Fr no. of 0.25. SIT did not sample at the speed with the highest $C_r$ and therefore missed the peak. The peak $C_r$ for the mid-inboard configuration occurs at a lower Froude no. than for the aft-mid configuration.

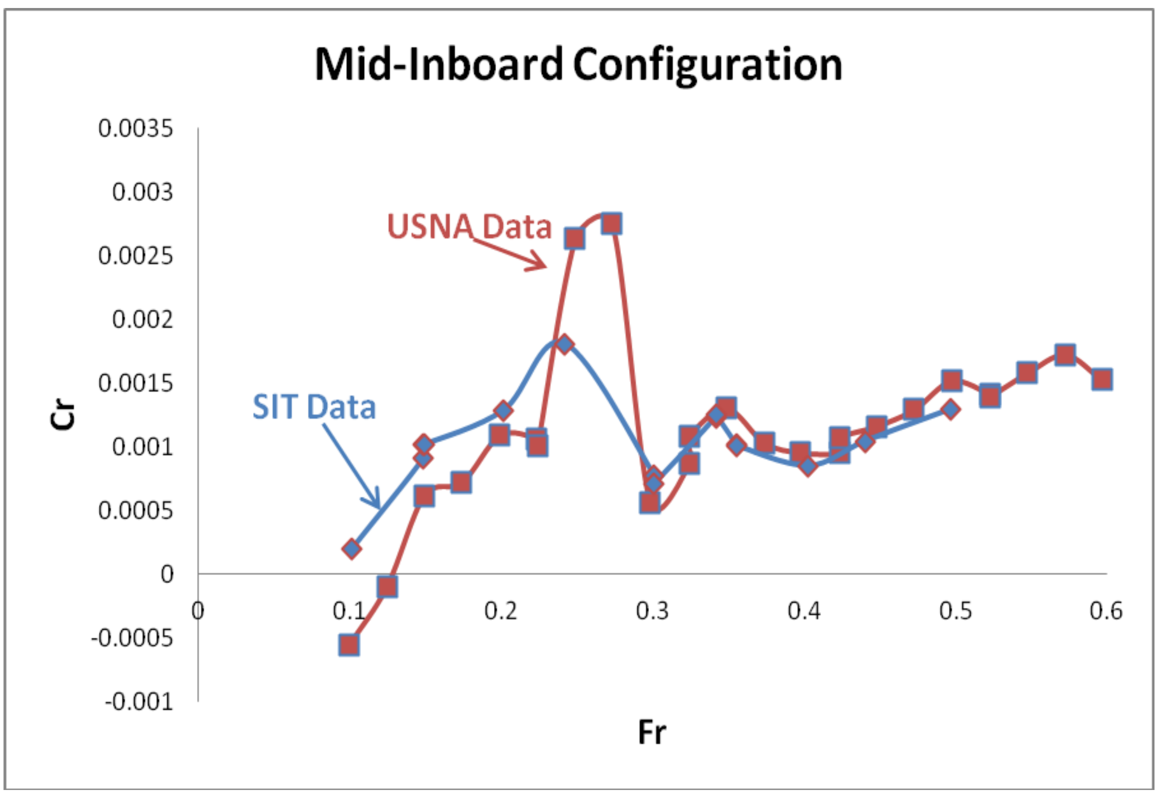


**Figure 12: Calm Water Towing Tank Correlation for Mid-Inboard Location**

### Parallel vs. Splayed Sidehull

This analysis examines the effect of splaying the sidehulls outboard on residuary resistance. Figure 13 shows $C_r$ against Froude no. for the three different splay conditions in the aft-mid configuration. This data set has the same issue with inconsistent turbulence stimulation below a Froude no. of 0.25, but there is good trending between the different splay conditions for higher speeds. At the Fr no. corresponding to the peak $C_r$ any amount of splay increases resistance, but at higher speeds some amount of splay may decrease $C_r$.

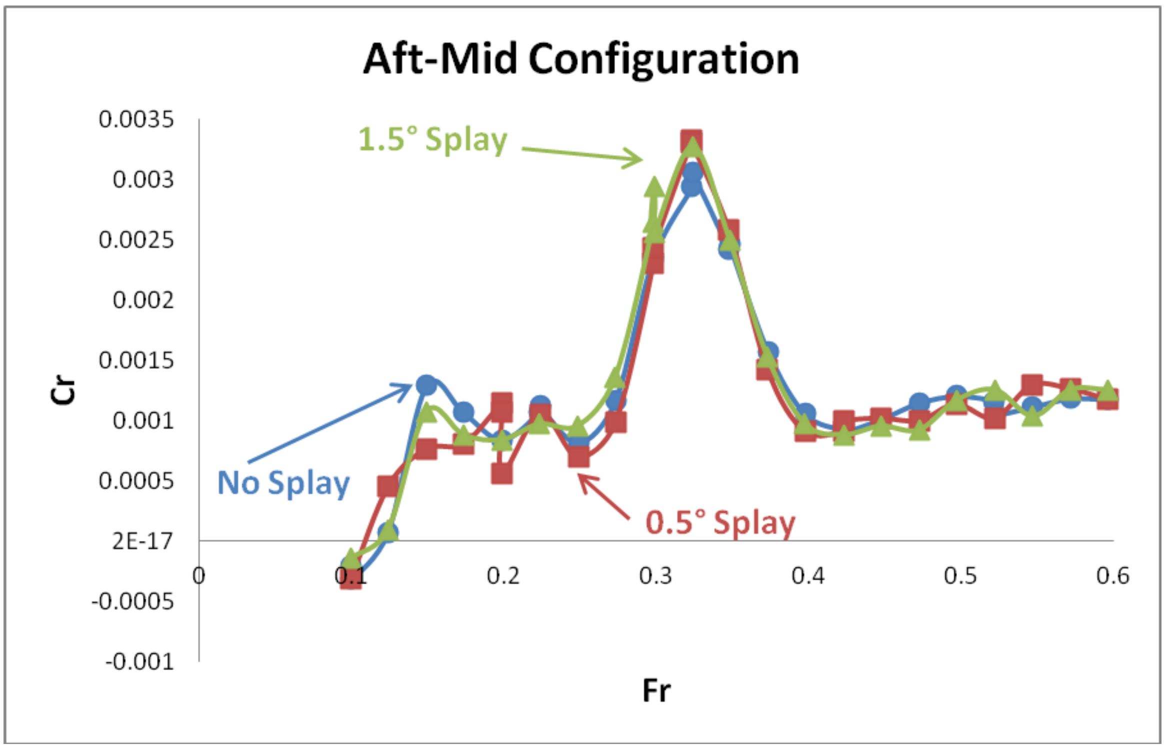


**Figure 13: Measured Effect of Splay for Aft-Mid Configuration**

Figure 14 shows curves of measured $C_r$ against Froude no. for the three different splay conditions in the mid-inboard configuration. At the Fr. no. for peak $C_r$ and at higher speeds a splay of 0.5 degrees shows some reduction of the residuary resistance, but splay of 1.5 degrees appears to increase $C_r$ throughout the tested speed range.

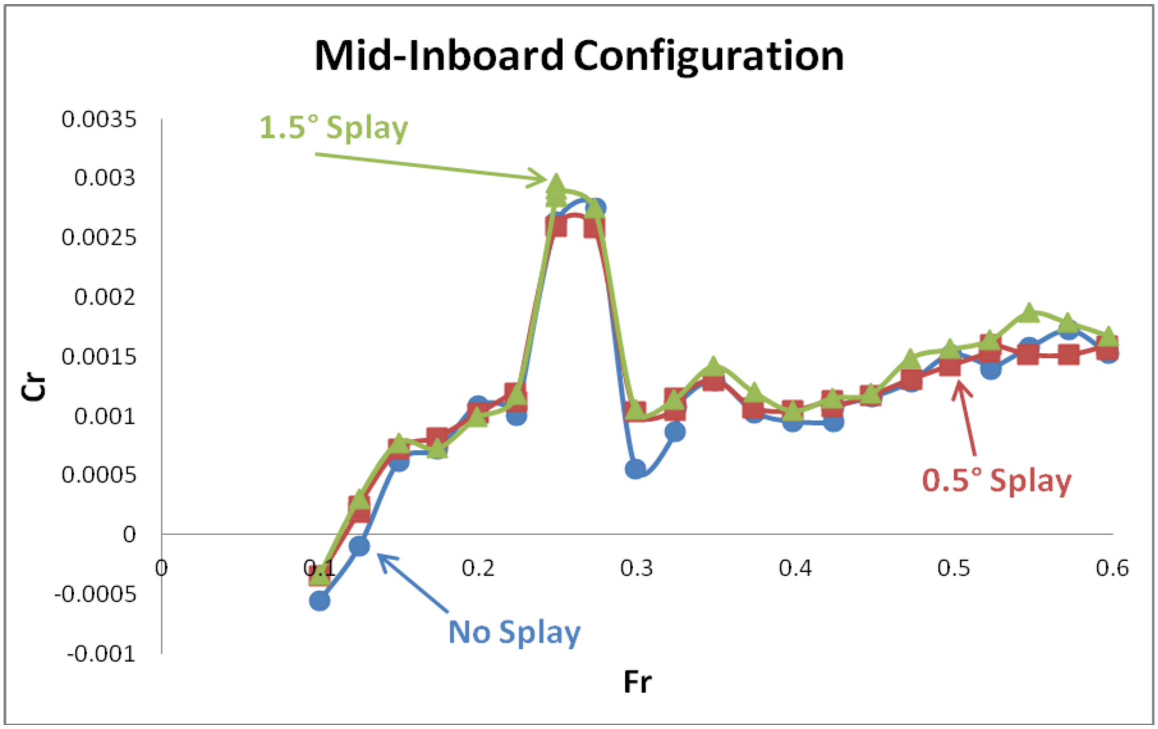


**Figure 14: Measured Effect of Splay for Mid-Inboard Configuration**

At a Froude no. of 0.3 there is a relatively large difference between the measured data for the splayed configurations and the non-splayed. Figure 15 compares data for all USNA splayed conditions for the mid-inboard position with the SIT non-splayed data for that configuration. Both the USNA and SIT non-splayed data have a local minimum at Froude no. of 0.3. This leads to the tentative conclusion that any amount of splay at that Fr. no. will increase the residuary resistance.

### Effect of Increasing Sidehull Displacement

This analysis compares the coefficient of residuary resistance for calm water testing of the model with the original sidehulls against the model configured with the double displacement sidehulls. The waterline of the centerhull in the original sidehull configuration and the double displacement sidehull configuration was held constant; this keeps the shape of the hull beneath the water line the same which is useful for the CFD hull form optimization tools.

Figure 15 compares the $C_r$ curves for the model with double displacement sidehulls and the model with the original sidehulls in the aft-mid configuration. The same issue with inconsistent turbulence stimulation probably caused the difference in trending below Froude no. of 0.25, but above that speed the trending between the two data sets confirms the repeatability of set-up between the two sidehull options. The $C_r$ for the double-displacement sidehull configuration is larger at the peak in the resistance curve as well as throughout the higher Froude numbers. Multiple runs at the Froude no. with peak resistance were performed to verify the results.

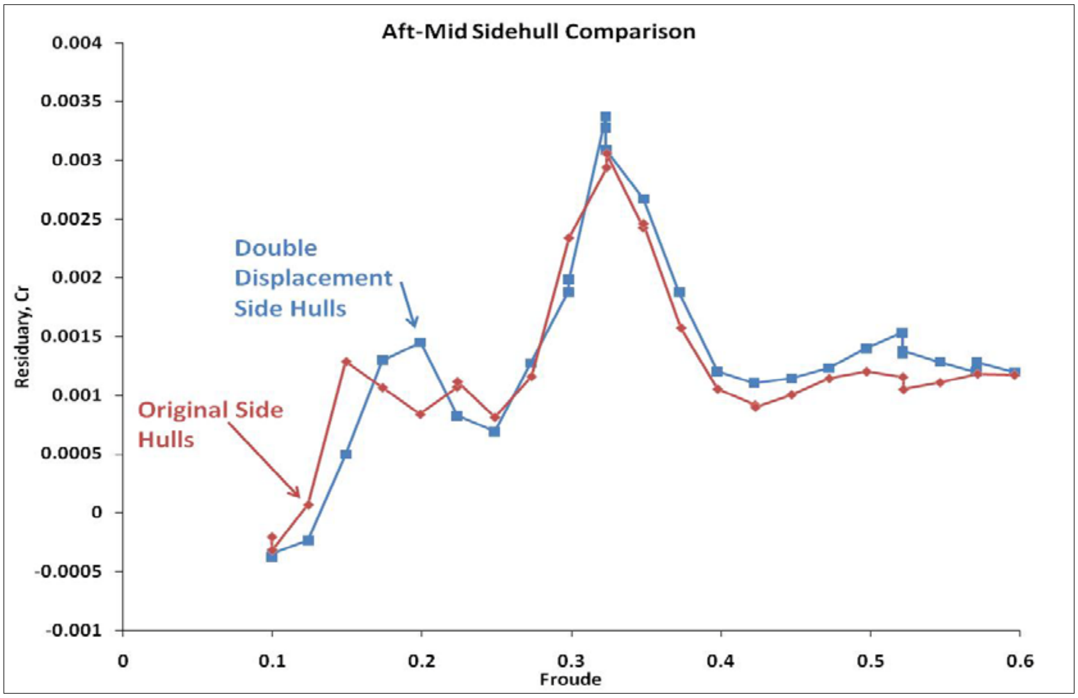


**Figure 15: $C_r$ for Single & Double Displacement Sidehulls for Aft-Mid Configuration**

Figure 16 is a comparison of $C_r$ curves for the model with two different sidehulls for the mid-inboard configuration. Unlike the comparison for the aft-mid configuration, the original sidehull model data for the mid-inboard configuration has a slightly larger peak $C_r$ value than that for the double displacement sidehull setup. At higher Froude no.'s, however, the double displacement sidehulls setup has a higher $C_r$ than that for the original sidehulls setup, as was true with the aft-mid configuration. For both sidehulls, the peak $C_r$ occurs at a lower Froude no. for the mid-inboard configuration than the aft-mid configuration.

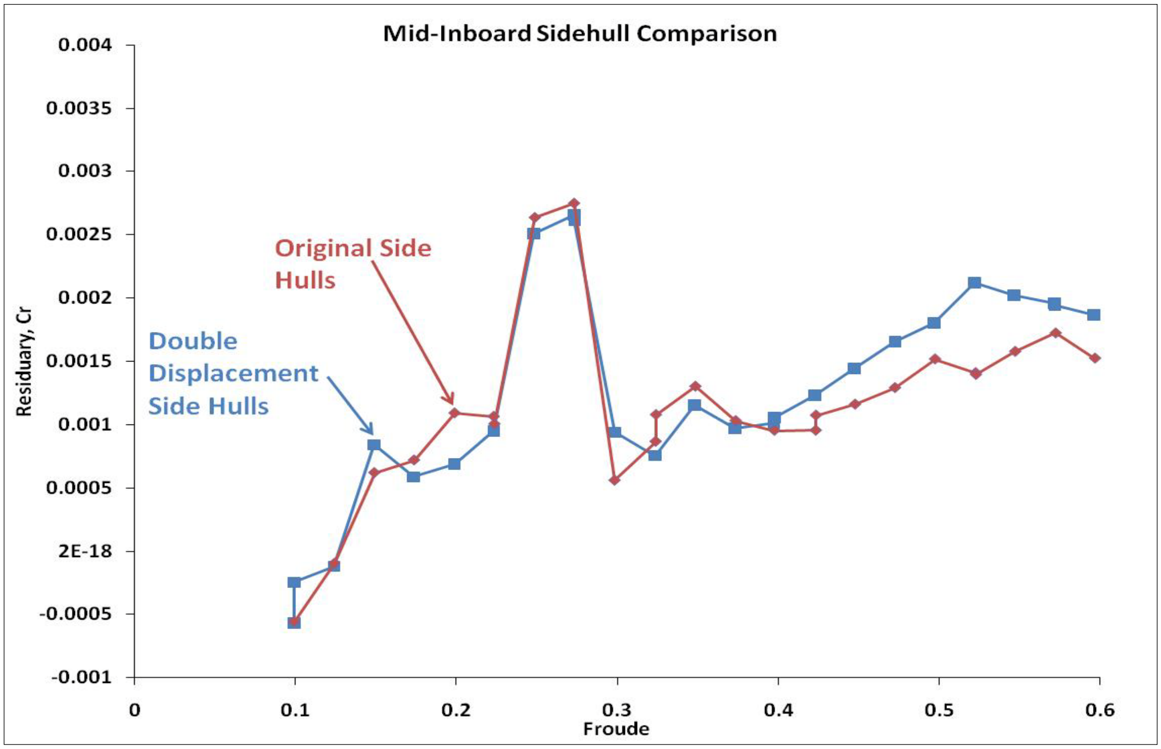


**Figure 16: $C_r$ for Single & Double Displacement Sidehulls for Mid-Inboard Configuration**

## EHP

Predicted effective horse power was calculated using the coefficient of residuary resistance generated from the calm water runs for the model fitted with the original sidehulls as well as runs with the double displacement sidehulls. The model resistance was scaled up to the resistance for a 1,000 LT ship, using a linear scale factor of 43. A correlation allowance ($C_A$) of 0.0004 was added to the ITTC friction line coefficient to account for full-scale roughness. In Figure 17 the scaled EHP is plotted as a function of speed for a 1,000 LT ship with the original sidehulls at the 2 tested positions. In the mid speed range of 17-21 knots, there is a hump in the curves where the aft-mid configuration requires more power than the mid-inboard configuration. Above 26 knots, the trend is reversed and the aft-mid configuration is more efficient. The maximum EHP values for the original sidehull configurations are approximately 15,000 horsepower at 34 knots.

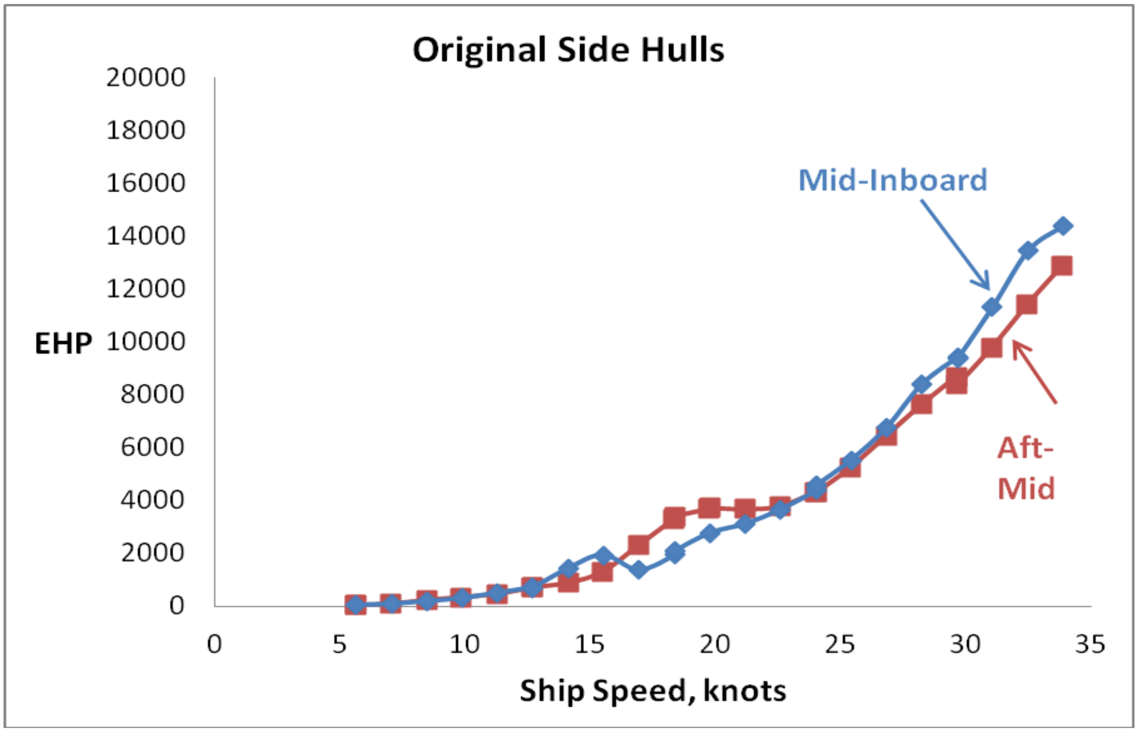


**Figure 17: Predicted EHP for 1,000 LT TriSWACH with Original Sidehulls**

Figure 18 is a similar comparison of predicted EHP for a 1,000 LT TriSWACH with the double displacement sidehulls in the two tested configurations. As with the EHP for the original sidehulls, there is a hump in the curves in the mid speed range, 18 to 23 knots, where the aft-mid configuration requires more power than the mid-inboard configuration. Above 24 knots, the aft-mid configuration is again more efficient. The maximum EHP values for the double displacement sidehull configurations are around 18,000 horsepower at 34 knots, which is a 20% increase over the EHP necessary with the original sidehulls.

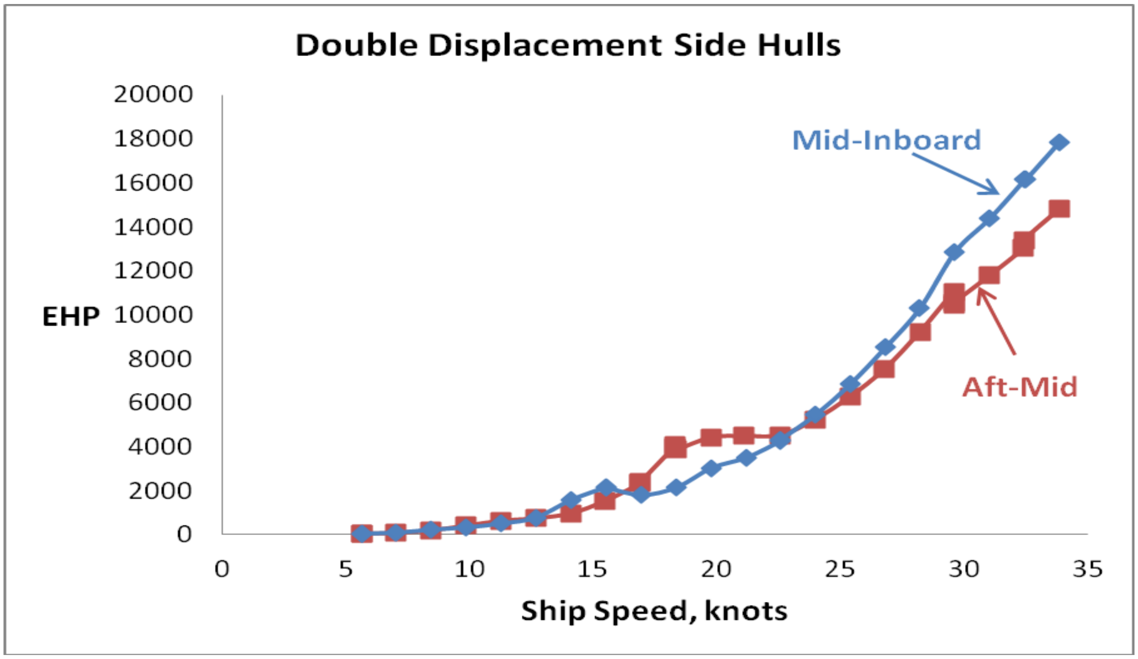


**Figure 18: Predicted EHP for 1,000 LT TriSWACH with Double Displacement Sidehulls**

## Seakeeping Tests

Regular and irregular wave testing was completed using the double displacement sidehulls in the aft-mid and mid-inboard configuration. Heave, pitch, resistance, vertical accelerations, and wave height data was collected. This testing was completed at the end of this team's available project time but the measured data will be analyzed by future ACCeSS project teams.

The vertical accelerations at the LCG were analyzed in real time during testing. Figure 19 shows a time history of the vertical accelerations and a time history of the velocity. Figure 19 shows an irregular wave data collection run in North Atlantic sea state 4 at Froude no. 0.3. These measured accelerations had the largest magnitude of all the seakeeping tests. The red and blue vertical lines mark the beginning and end of the time frame when the model velocity was in steady state. The maximum acceleration observed during this time frame was 0.16 g's. This is well below the NAVSEA criterion of a 0.4 g maximum significant single amplitude. (Colen G. Kennell, 1985)

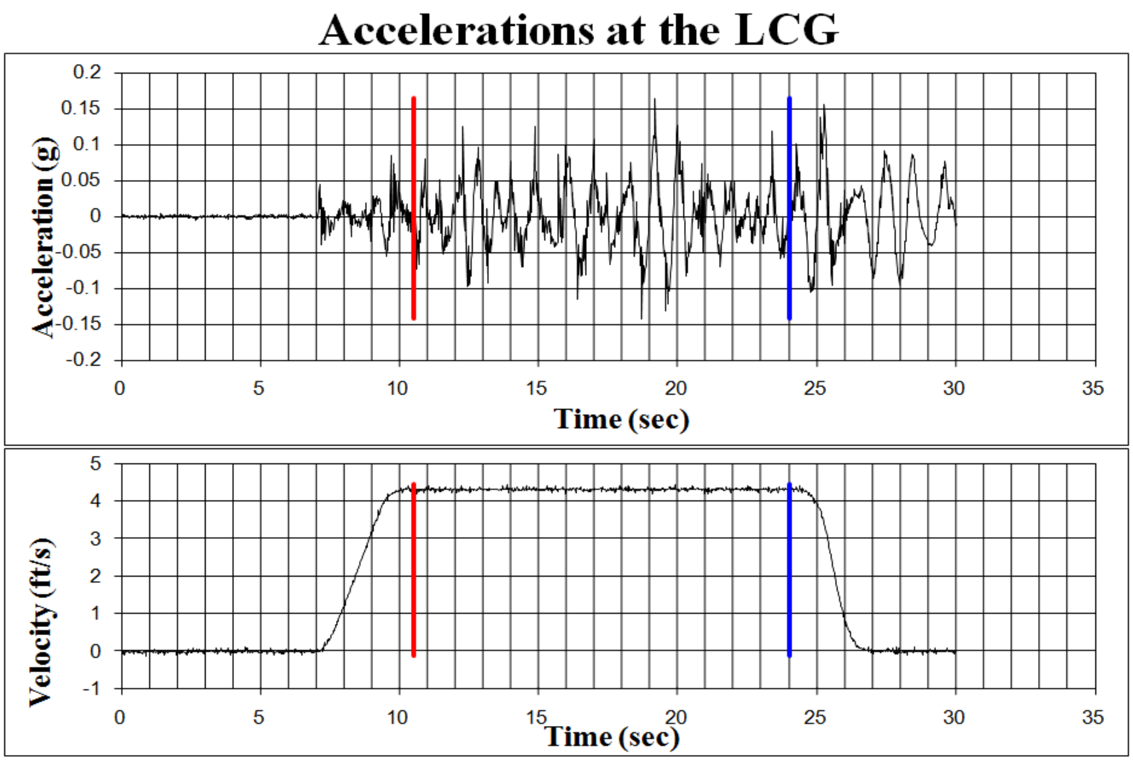


**Figure 19: Aft-Mid LCG Accelerations at Fn = 0.3 in sea state 4 Head Seas**

## Challenges

The largest challenge for this project was time. The team was not able to begin testing in the tow tank until the 5th week of the 10 week project. However, the team used the time before testing to complete an Excel document to analyze the resistance data in real time as well as to design a method for accurately changing the model setup with minimal down time. This method aided the team in completing over 300 successful data collection runs in 3 weeks.

A further challenge was the model itself. The small size of the model limited the amount of available weight which could be added, which made ballasting the model in all sidehull configurations very challenging. The team had to tow the model from a position forward of the LCG in order to correctly ballast the model with the sidehulls in the furthest aft position. The analysis of the heave data will be more complicated because the heave post was measuring heave at the towing position, not at the LCG. Towing the model from a point forward of the LCG also

complicated the gyradius testing. The weight of the heave post assembly can normally be ignored when using the Lamboley method because it is centered at the LCG, but because the heave post mount was forward of the LCG it had to be included in the calculations.

## Summary and Conclusions

The primary objective of this project was to expand the TriSWACH testing database and this goal was successfully satisfied. In gathering over 300 successful data collection runs, previous testing was validated and new test parameters were explored. Retesting of the previous tests completed by SIT found good agreement on trends between the two data sets, which validates the previous results and also confirms the soundness of the team's testing procedure.

The testing database was expanded to include data from many previously untested configurations. The effect of splaying the sidehulls 0.5 and 1.5 degrees outboard was examined. Comparing these results with those for the parallel condition, it appears splay may have some resistance reduction benefits depending on the sidehull configuration and ship speed. The indexing blocks designed by the team allow for rapid and accurate set up of the sidehulls in different splay conditions, and can be used by future testing teams to further explore this concept.

The effect of increasing the displacement of the sidehulls was investigated for the first time. The two different sets of sidehulls seem to have similar wave making characteristics, but the double-displacement sidehulls created more residuary resistance at higher speeds than the original sidehulls. However, the larger sidehulls do increase transverse stability for a given transverse hull separation.

Resistance data was gathered for the individual hulls tested independently. This was done so that future teams can use this data to study the interference between the hulls for each configuration. This will be done by comparing the resistance values gathered by testing the complete model with the total resistance calculated by adding the resistance of each hull when run in isolation.

The data from the centerhull run in isolation will be used to validate CFD hull form optimization tools that are currently being developed.

Seakeeping testing was completed for both regular and irregular waves. The recorded data included heave, pitch, total model resistance, wave heights, and vertical accelerations at the LCG and at the bow. This testing was completed at the very end of the allotted project timeframe and will be analyzed by future teams. Preliminary analysis of the vertical accelerations at the LCG shows accelerations well within NAVSEA guidelines.

## Suggestions for Future Work

The testing matrix for this project involved testing the model with the sidehulls in the aft-mid and the mid-inboard configuration. Future projects should involve expanding the database with calm water and seakeeping tests with the double displacement sidehulls in the other possible sidehull positions. The double displacement sidehulls should also be tested in the splayed condition for comparison with original sidehulls with splay, as well as testing different levels of splay both inboard and outboard for both sets of sidehulls. A flow visualization study of the sidehulls in the splayed condition would benefit the understanding of how to best splay the sidehulls for optimal performance.

## References

Colen G. Kennell, B. L. (1985). Innovative Naval Designs for North Atlantic Operations. *SNAME Transactions* , 261-281.

Hoerner, D. L. (1965). *Fluid-Dynamic Drag* . Bakersfield, CA: Published by Author.

Justin Klag, I. M. *CALM WATER RESISTANCE STUDY OF A NOVEL TRIMARAN*. Glen Cove, New York: Webb Institute.

Lloyd, A. R. (1989). *Seakeeping: Ship Behaviour in Rough Weather*. Horwood, Chichester, UK : A R J M Lloyd; 2nd Revised edition.

White, G. (n.d.). Lab Manual. *EN455 Seakeeping & Maneuvering Lab#5 Dynamic Ballasting* . Annapolis, MD: USNA.

# Appendices

## Appendix A: Indexing Blocks

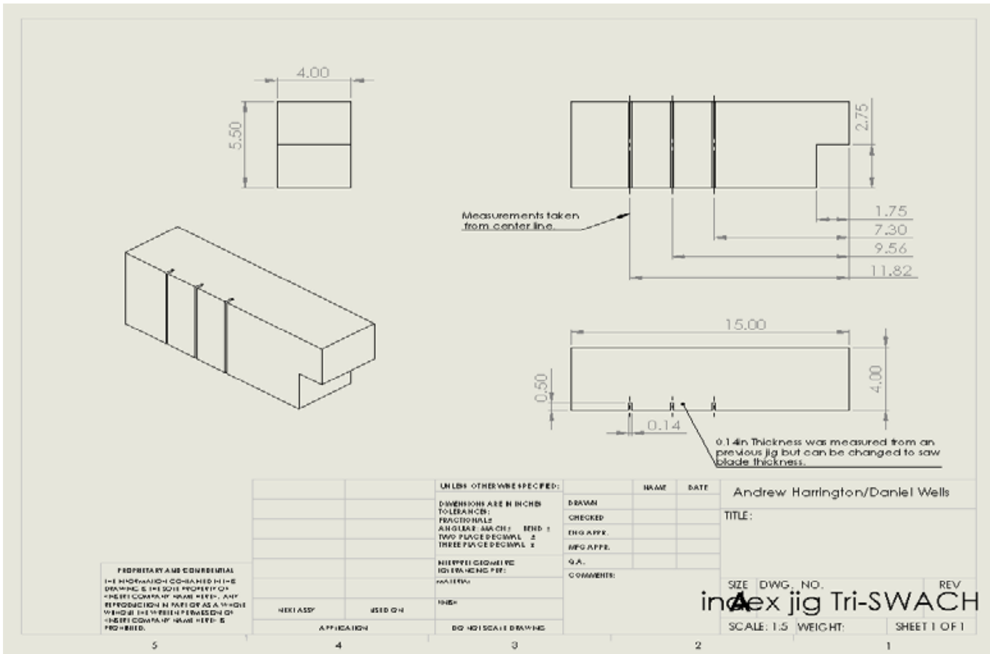


Figure 20: Solid Works Drawing Of Indexing Block

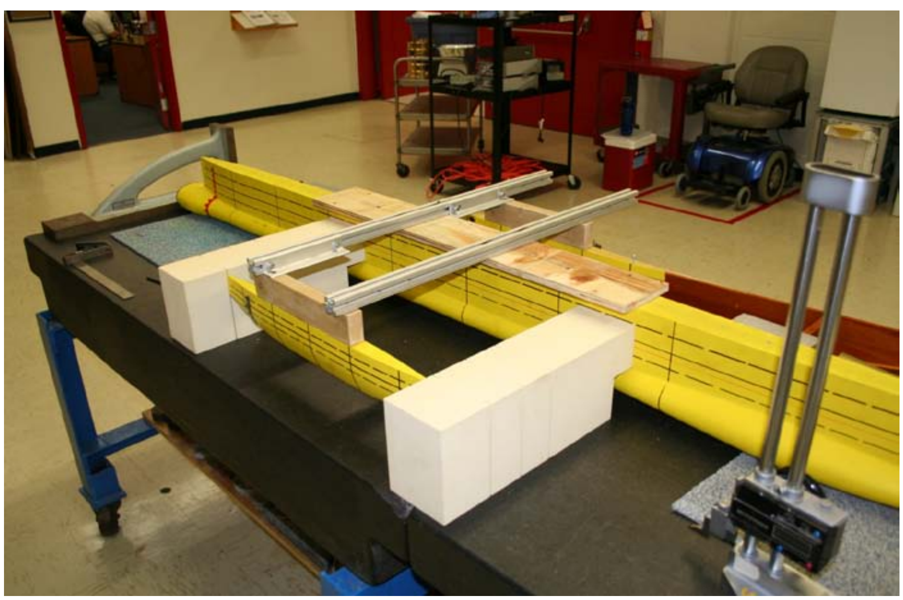

Figure 21: Model Setup Using Indexing Blocks

# Appendix B: Hama Strip Calculation

USNA Hydrodynamics lab spreadsheets loaned to the team for this project

| | A | B | C | D | E | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | TRI-SWACH Model Testing--USNA Hydro Lab Summer 2011 | | | | | | | | | | |
| 2 | Hama Strip Sizing | | | | | | | | | | |
| 3 | Reference - Low Speed Wind Tunnel Testing by Barlow, Rae and Pope, pgs. 309-310, John Wiley and Sons Inc, 1999 | | | | | | | | | | |
| 4 | **Original Sidehull** | | | | | | | | | | |
| 5 | V | 5 | fps | | | | | | | | |
| 6 | L | 1.79 | ft | | 21.48 | in | 1.79 | | | | |
| 7 | visc | 1.07E-05 | | Fresh $H_2O$- 68° F | | | | | | | |
| 8 | Trip Location | 10.0 | (%chord) | | | | | | | | |
| 9 | | 1.00E+01 | | | | | | | | | |
| 10 | | | | | | | | | | | |
| 11 | Rn | 8.36E+05 | | | | | | | | | |
| 12 | Rn/ft | 4.67E+05 | | | | | | | | | |
| 13 | Rn at Trip | 8.36E+04 | | | | | | | | | |
| 14 | | | | | | | | | | | |
| 15 | Height of Hama Strip | | 0.026 | inches | | | | | | | |
| 16 | Location of Hama Strip | | 2.148 | inches aft LE | | | | | | | |
| 17 | | | | | | | | | | | |
| 18 | One layer of Vinyl Tape is 0.005 inches thick | | | | | | | | | | |
| 19 | | | | | | | | | | | |
| 20 | # of layers | 5.136 | | | 5 | layers use | 0.025 | in | actual thickness | | |
| 21 | | | | | | | | | | | |
| 22 | Length of Hama Strip (Deck to Deck) | | | | | | | | | | |
| 23 | Starboard | 4.72 | in | | | | | | | | |
| 24 | Port | 4.6 | in | | | | | | | | |
| 25 | | | | | | | | | | | |
| 26 | | | | | | | | | | | |
| 27 | | | | | | | | | | | |

**Figure 22: Center Hull Hama Strip Calculation**

| | A | B | C | D | E | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | TRI-SWACH Model Testing--USNA Hydro Lab Summer 2011 | | | | | | | | | | |
| 2 | Hama Strip Sizing | | | | | | | | | | |
| 3 | Reference - Low Speed Wind Tunnel Testing by Barlow, Rae and Pope, pgs. 309-310, John Wiley and Sons Inc, 1999 | | | | | | | | | | |
| 4 | **Centerhull** | | | | | | | | | | |
| 5 | V | 5 | fps | | | | | | | | |
| 6 | L | 6.63275 | ft | | 79.593 | in | 6.63275 | | | | |
| 7 | visc | 1.07E-05 | | Fresh $H_2O$- 68° F | | | | | | | |
| 8 | Trip Location | 10.0 | (%chord) | | | | | | | | |
| 9 | | 1.00E+01 | | | | | | | | | |
| 10 | | | | | | | | | | | |
| 11 | Rn | 3.10E+06 | | | | | | | | | |
| 12 | Rn/ft | 4.67E+05 | | | | | | | | | |
| 13 | Rn at Trip | 3.10E+05 | | | | | | | | | |
| 14 | | | | | | | | | | | |
| 15 | Height of Hama Strip | | 0.015 | inches | | | | | | | |
| 16 | Location of Hama Strip | | 7.9593 | inches aft LE | | | | | | | |
| 17 | | | | | | | | | | | |
| 18 | One layer of Vinyl Tape is 0.005 inches thick | | | | | | | | | | |
| 19 | | | | | | | | | | | |
| 20 | # of layers | 3.0816 | | | 3 | layers use | 0.015 | in | actual thickness | | |
| 21 | | | | | | | | | | | |
| 22 | Length of Hama Strip (Waterline to Waterline) | | | | | | | | | | |
| 23 | 21.2 | in | | | | | | | | | |
| 24 | | | | | | | | | | | |
| 25 | | | | | | | | | | | |
| 26 | | | | | | | | | | | |
| 27 | | | | | | | | | | | |
| 28 | | | | | | | | | | | |
| 29 | | | | | | | | | | | |

**Figure 23: Original Sidehull Hama Strip Calculation**

| | A | B | C | D | E | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | TRI-SWACH Model Testing--USNA Hydro Lab Summer 2011 | | | | | | | | | | |
| 2 | Hama Strip Sizing | | | | | | | | | | |
| 3 | Reference - Low Speed Wind Tunnel Testing by Barlow, Rae and Pope, pgs. 309-310, John Wiley and Sons Inc, 1999 | | | | | | | | | | |
| 4 | **Double Displacement Sidehull** | | | | | | | | | | |
| 5 | V | 5 | fps | | | | | | | | |
| 6 | L | 2.25833 | ft | | 27.1 | in | 2.258333 | | | | |
| 7 | visc | 1.06E-05 | | Fresh $H_2O$- 68° F | | | | | | | |
| 8 | Trip Location | 10.0 | (%chord) | | | | | | | | |
| 9 | | 1.00E+01 | | | | | | | | | |
| 10 | | | | | | | | | | | |
| 11 | Rn | 1.07E+06 | | | | | | | | | |
| 12 | Rn/ft | 4.72E+05 | | | | | | | | | |
| 13 | Rn at Trip | 1.07E+05 | | | | | | | | | |
| 14 | | | | | | | | | | | |
| 15 | Height of Hama Strip | | 0.015 | inches | | | | | | | |
| 16 | Location of Hama Strip | | 2.709996 | inches aft LE | | | | | | | |
| 17 | | | | | | | | | | | |
| 18 | One layer of Vinyl Tape is 0.005 inches thick | | | | | | | | | | |
| 19 | | | | | | | | | | | |
| 20 | # of layers | 3.0528 | | | 3 | layers use | 0.015 | in | actual thickness | | |
| 21 | | | | | | | | | | | |
| 22 | Length of Hama Strip (Total length of tape) | | | | | | | | | | |
| 23 | Starboard | 5.18 | in | | | | | | | | |
| 24 | Port | 5.18 | in | | | | | | | | |
| 25 | | | | | | | | | | | |
| 26 | | | | | | | | | | | |
| 27 | | | | | | | | | | | |

**Figure 24: Double Displacement Sidehull Hama Strip Calculation**

# Appendix C: Instrumentation Calibrations

| | | | | |
|---|---|---|---|---|
| NAHL Calibration of: | Heave | | | |
| Least Squares Fit of Calibration Data | | | | |
| Full Scale Gage Capacity (FS): | 4 in | | | |
| Date: | 6/27/2011 | | | |

**U.S. Naval Academy**
Hydromechanics Laboratory
590 Holloway Road
Annapolis, MD 21402

| Applied Load in | Gage Output volts | Fit Output volts | Difference in | Percent Full Scale |
|---|---|---|---|---|
| 0.00 | 0.001 | -0.01 | -0.0035 | -0.087 |
| -0.25 | -0.508 | -0.50 | 0.0031 | 0.077 |
| -0.50 | -1.003 | -1.00 | 0.0025 | 0.062 |
| -0.75 | -1.498 | -1.49 | 0.0020 | 0.050 |
| -1.00 | -1.996 | -1.99 | 0.0029 | 0.071 |
| 0.25 | 0.502 | 0.49 | -0.0060 | -0.151 |
| 0.50 | 0.986 | 0.99 | -0.0001 | -0.003 |
| 0.75 | 1.479 | 1.48 | 0.0013 | 0.033 |
| 1.00 | 1.966 | 1.98 | 0.0059 | 0.148 |
| 0.00 | 0.001 | -0.01 | -0.0039 | -0.097 |
| -0.50 | -1.007 | -1.00 | 0.0045 | 0.112 |
| 0.25 | 0.502 | 0.49 | -0.0062 | -0.155 |
| 0.75 | 1.479 | 1.48 | 0.0011 | 0.028 |
| 1.00 | 1.967 | 1.98 | 0.0054 | 0.134 |
| 0.25 | 0.501 | 0.49 | -0.0058 | -0.145 |
| 0.00 | 0.000 | -0.01 | -0.0032 | -0.080 |

| | |
|---|---|
| Gage No. | |
| Amp No. | |
| Gage Cal | |
| Gain | |
| Cal Pot | |
| Cable ID | |

| | | |
|---|---|---|
| **Gage Sensitivity:** | 1.9837 | **volts / in** |
| Offset: | -0.00638 | volts |

Calibration Linearity Statistics:

| | | |
|---|---|---|
| **Max Deviation:** | 0.155 | **% Full Scale** |
| Max Deviation: | 0.006 | in |
| Std. Deviation: | 0.0040 | in |

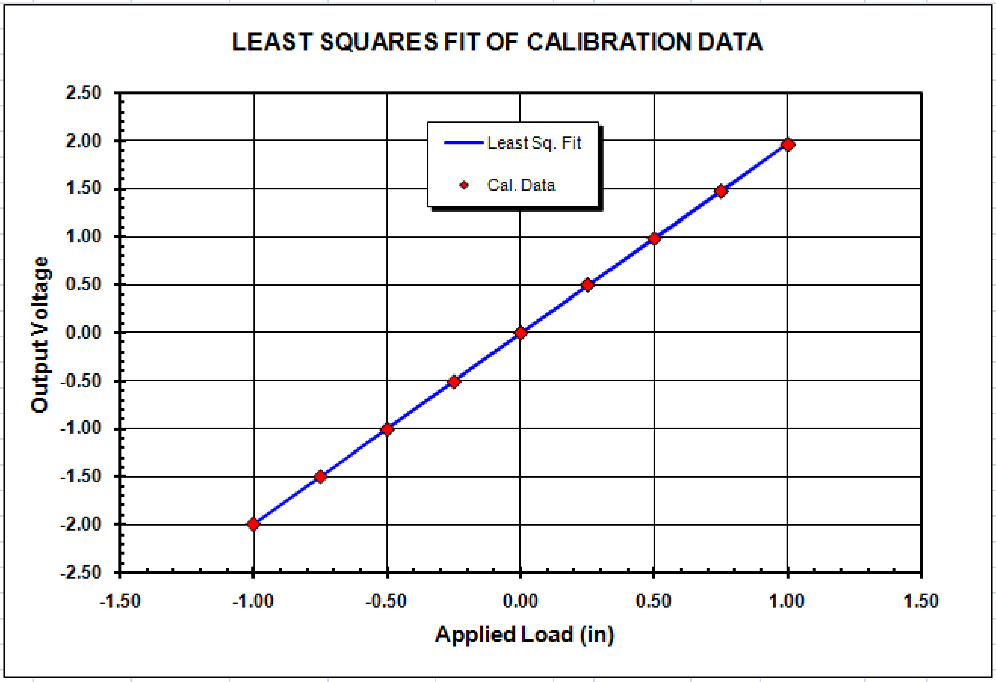


Figure 25: Heave Gauge Calibrations

NAHL Calibration of: Pitch
Least Squares Fit of Calibration Data
Full Scale Gage Capacity (FS): 30 deg
Date: 9/27/2011

**U.S. Naval Academy**
Hydromechanics Laboratory
590 Holloway Road
Annapolis, MD 21402

| Applied Load deg | Gage Output volts | Fit Output volts | Difference deg | Percent Full Scale |
|---|---|---|---|---|
| 0.00 | -0.001 | -0.01 | 0.0176 | 0.059 |
| -1.00 | 0.395 | 0.38 | 0.0358 | 0.119 |
| -2.00 | 0.759 | 0.77 | -0.0305 | -0.102 |
| -3.00 | 1.170 | 1.16 | 0.0257 | 0.086 |
| -4.00 | 1.534 | 1.55 | -0.0380 | -0.127 |
| 0.00 | 0.006 | -0.01 | 0.0345 | 0.115 |
| 1.00 | -0.388 | -0.40 | 0.0222 | 0.074 |
| 2.00 | -0.777 | -0.79 | 0.0251 | 0.084 |
| 3.00 | -1.183 | -1.18 | -0.0181 | -0.060 |
| 4.00 | -1.567 | -1.56 | -0.0067 | -0.022 |
| 0.00 | -0.007 | -0.01 | 0.0032 | 0.011 |
| -2.00 | 0.763 | 0.77 | -0.0202 | -0.067 |
| 1.00 | -0.404 | -0.40 | -0.0186 | -0.062 |
| 3.00 | -1.187 | -1.18 | -0.0304 | -0.101 |
| 4.00 | -1.564 | -1.56 | 0.0012 | 0.004 |
| 1.00 | -0.407 | -0.40 | -0.0266 | -0.089 |
| 0.00 | 0.001 | -0.01 | 0.0238 | 0.079 |

| | |
|---|---|
| Gage No. | |
| Amp No. | |
| Gage Cal | |
| Gain | |
| Cal Pot | |
| Cable ID | |

**Gage Sensitivity:** -0.3892 **volts / deg**
Offset: -0.00784 volts

Calibration Linearity Statistics:

| | | |
|---|---|---|
| **Max Deviation:** | **0.127** | **% Full Scale** |
| Max Deviation: | 0.038 | deg |
| Std. Deviation: | 0.0246 | deg |

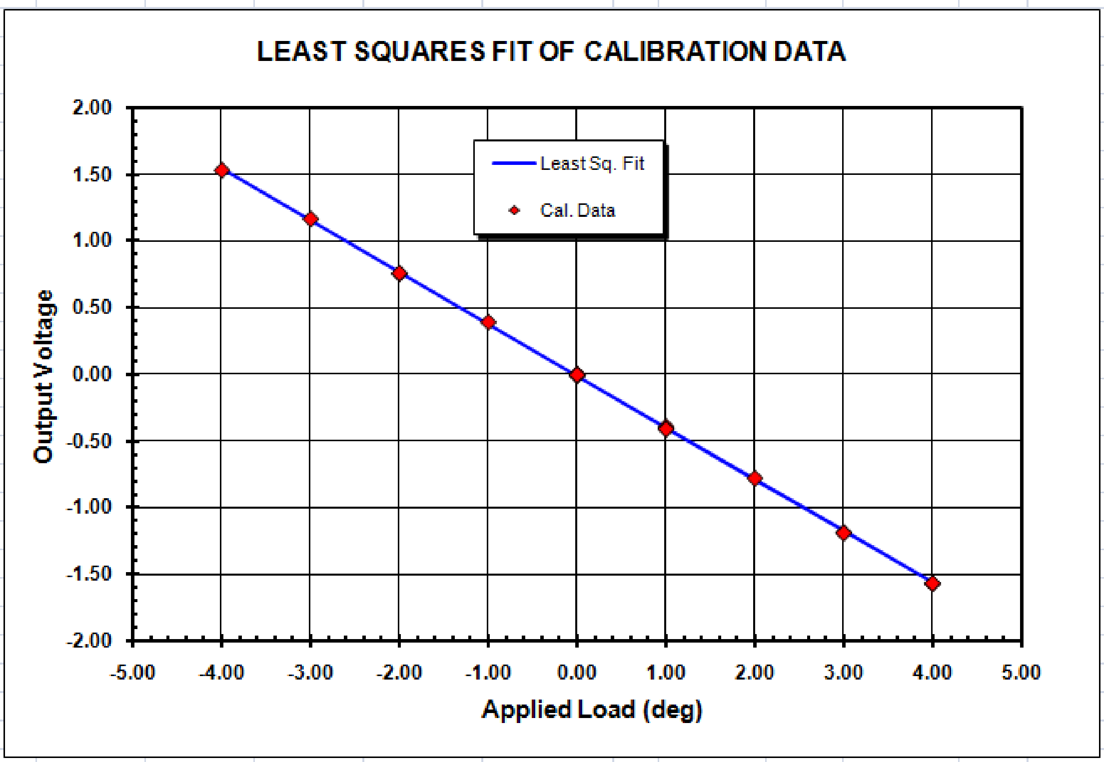


**Figure 26: Pitch Pivot Gauge**

NAHL Calibration of: 10 lb Block Gauge (Total)
Least Squares Fit of Calibration Data
Full Scale Gage Capacity (FS): 10 lb
Date:

**U.S. Naval Academy**
Hydromechanics Laboratory
590 Holloway Road
Annapolis, MD 21402

**Total Resistance Block Gauge**

| Applied Load lb | Gage Output volts | Fit Output volts | Difference lb | Percent Full Scale |
|---|---|---|---|---|
| 10.00 | -6.210 | -6.20 | -0.0122 | -0.122 |
| 9.00 | -5.570 | -5.58 | 0.0205 | 0.205 |
| 8.00 | -4.970 | -4.96 | -0.0114 | -0.114 |
| 7.00 | -4.350 | -4.34 | -0.0109 | -0.109 |
| 6.00 | -3.730 | -3.72 | -0.0105 | -0.105 |
| 5.00 | -3.100 | -3.10 | 0.0061 | 0.061 |
| 4.00 | -2.480 | -2.48 | 0.0065 | 0.065 |
| 3.00 | -1.860 | -1.86 | 0.0070 | 0.070 |
| 2.00 | -1.250 | -1.24 | -0.0087 | -0.087 |
| 1.00 | -0.630 | -0.62 | -0.0083 | -0.083 |
| 0.00 | -0.010 | -0.01 | -0.0079 | -0.079 |
| 7.00 | -4.340 | -4.34 | 0.0052 | 0.052 |
| 2.00 | -1.250 | -1.24 | -0.0087 | -0.087 |
| 5.00 | -3.100 | -3.10 | 0.0061 | 0.061 |
| 3.00 | -1.860 | -1.86 | 0.0070 | 0.070 |
| 9.00 | -5.580 | -5.58 | 0.0043 | 0.043 |
| 0.00 | 0.000 | -0.01 | 0.0083 | 0.083 |
| 1.00 | -0.620 | -0.62 | 0.0078 | 0.078 |
| 2.00 | -1.240 | -1.24 | 0.0074 | 0.074 |
| 3.00 | -1.850 | -1.86 | 0.0231 | 0.231 |
| 4.00 | -2.480 | -2.48 | 0.0065 | 0.065 |
| 5.00 | -3.100 | -3.10 | 0.0061 | 0.061 |
| 6.00 | -3.720 | -3.72 | 0.0056 | 0.056 |
| 7.00 | -4.330 | -4.34 | 0.0213 | 0.213 |
| 8.00 | -4.970 | -4.96 | -0.0114 | -0.114 |
| 9.00 | -5.570 | -5.58 | 0.0205 | 0.205 |
| 10.00 | -6.210 | -6.20 | -0.0122 | -0.122 |

| | |
|---|---|
| Gage No. | |
| Amp No. | |
| Gage Cal | |
| Gain | |
| Cal Pot | |
| Cable ID | |

**Gage Sensitivity:** -0.6197 **volts / lb**
Offset: -0.00512 volts

Calibration Linearity Statistics:

| | | |
|---|---|---|
| **Max Deviation:** | 0.205 | **% Full Scale** |
| Max Deviation: | 0.020 | lb |
| Std. Deviation: | 0.0098 | lb |

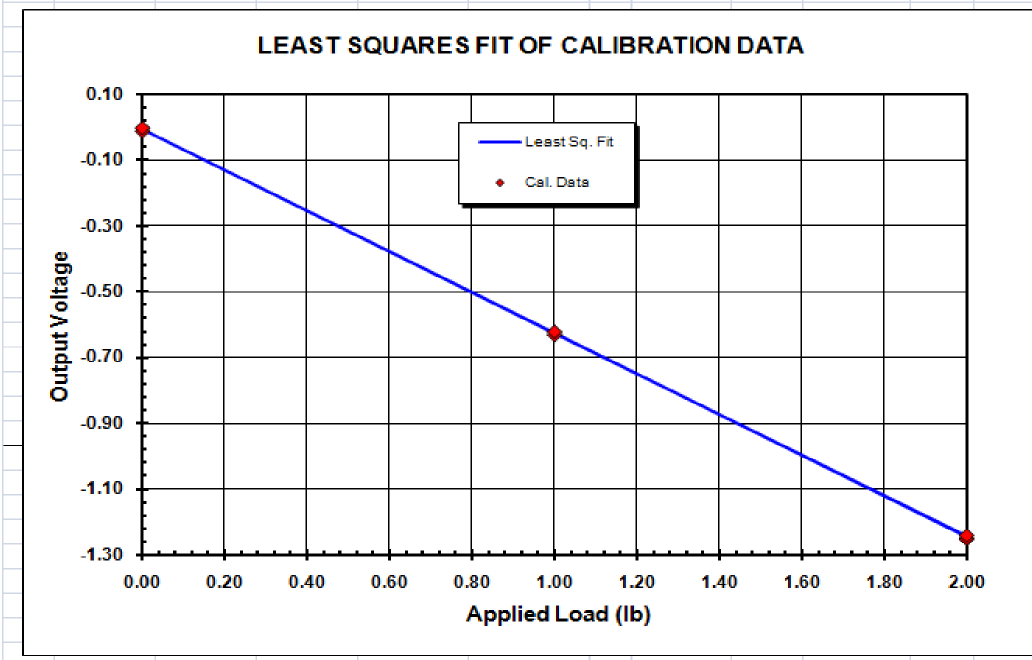


**Figure 27: Total Resistance Block Gauge Calibration**

NAHL Calibration of: 10 lb Block Gauge (Total 2)
Least Squares Fit of Calibration Data
Full Scale Gage Capacity (FS): 10 lb
Date:

**U.S. Naval Academy**
Hydromechanics Laboratory
590 Holloway Road
Annapolis, MD 21402

**Side Hull Block Gauge**

| Applied Load lb | Gage Output volts | Fit Output volts | Difference lb | Percent Full Scale |
|---|---|---|---|---|
| 0.00 | 0.000 | 0.00 | -0.0009 | -0.009 |
| 0.50 | 1.240 | 1.25 | 0.0021 | 0.021 |
| 1.00 | 2.490 | 2.49 | 0.0011 | 0.011 |
| 1.50 | 3.740 | 3.74 | 0.0001 | 0.001 |
| 2.00 | 4.990 | 4.99 | -0.0009 | -0.009 |
| 1.50 | 3.740 | 3.74 | 0.0001 | 0.001 |
| 0.50 | 1.250 | 1.25 | -0.0019 | -0.019 |

| | |
|---|---|
| Gage No. | |
| Amp No. | |
| Gage Cal | |
| Gain | |
| Cal Pot | |
| Cable ID | |

**Gage Sensitivity:** 2.4950 **volts / lb**
Offset: -0.00214 volts

Calibration Linearity Statistics:

| | | |
|---|---|---|
| **Max Deviation:** | **0.021** | **% Full Scale** |
| Max Deviation: | 0.002 | lb |
| Std. Deviation: | 0.0012 | lb |

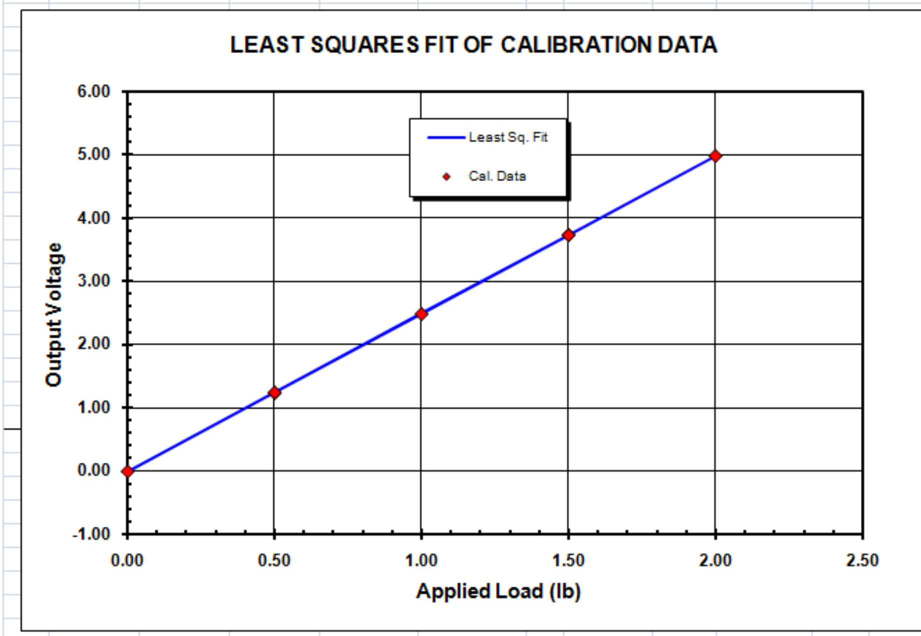


**Figure 28: Side Hull Block Gauge Calibration**

# Appendix D: North Atlantic Sea State

| Sea State Number | Significant Wave Height (FT) | | Sustained Wind Speed (Knots)* | | Percentage Probability Of Sea State | Modal Wave Period (sec) | |
|---|---|---|---|---|---|---|---|
| | Range | Mean | Range | Mean | | Range** | Most Probable*** |
| 0 – 1 | 0 – 0.3 | .15 | 0 – 6 | 3 | 0 | - | - |
| 2 | 0.3 – 1.6 | .95 | 7 – 10 | 8.5 | 7.2 | 3.3 – 12.8 | 7.5 |
| 3 | 1.6 – 4.1 | 2.85 | 11 – 16 | 13.5 | 22.4 | 5.0 – 14.8 | 7.5 |
| 4 | 4.1 – 8.2 | 6.15 | 17 – 21 | 19 | 28.7 | 6.1 – 15.2 | 8.8 |
| 5 | 8.2 – 13.1 | 10.65 | 22 – 27 | 24.5 | 15.5 | 8.3 – 15.5 | 9.7 |
| 6 | 13.1 – 19.7 | 16.40 | 28 – 47 | 37.5 | 18.7 | 9.8 – 16.2 | 12.4 |
| 7 | 19.7 – 29.5 | 24.60 | 48 – 55 | 51.5 | 6.1 | 11.8 – 18.5 | 15.0 |
| 8 | 29.5 – 45.9 | 37.70 | 56 – 63 | 59.5 | 1.2 | 14.2 – 18.6 | 16.4 |
| > 8 | > 45.9 | > 45.90 | > 63 | >63 | <0.05 | 15.7 – 23.7 | 20 |

* Ambient wind sustained at 19.5 m above the surface to generate fully-developed seas. To convert to another altitude, H2, apply $V_2 = V_1 (H_2/19.5)^{1/7}$

** Minimum is 5 percentile and maximum is 95 percentile for periods given wave height range.

*** Based on periods associated with central frequencies included in Hindcast Climatology.

**Figure 29: North Atlantic Sea State**